APPENDIX 2

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For: MICROMECHANICAL MONOCHROMATOR WITH INTEGRATED SLIT APERTURE FOR MICROSPECTROMETERS IN THE UV, VISIBLE AND INFRARED RANGE

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TRANSLATION OF DE 199 55 759 A1

A Spectrometer with a Micromechanical Mirror

Description

[0001] The concept of the invention lies within the field of optical spectroscopy and specifically relates to an arrangement for the simplification of the construction of grid based monochromators, to which mechanical parameters may be applied.

[0002] More exactly defined, the invention includes special monochromators, which consist of: at least one positionally fixed, spatial filter for the limitation of solid angle zones of an incident polychromatic beam, a dispersive element for the spectrally related, spatial angle alterations of the said beam as well as at least one additional, positionally fixed spatial filter for the removal of monochromatic beam fragments which are to be found in the spatial angle zone. In this relationship, additional means for controllable, beam-geometric, spatial angle changing of the beam are available.

[0003] Normally, dispersive elements comprise prisms or diffraction gratings. The spatial filter, most proximal to the point of incidence, is mostly made from a slit membrane in combination with imaging elements, namely, for example, lens systems, and/or a concave mirror and said filters generally serve for the collimation, within a narrow angular range, of the incident, polychromatic, radiation. In many cases,

the dispersive agent itself can be made to act in an imaging manner in its optical treatment of the radiation, by means of, for example, a concave grating.

[0004] Analogously, the output, or exit side space filter consists of an imaging means in combination with an exit slot orifice structure, which limits the spatial angle zone, by means of which the said beam fragments with their correspondingly, directional specific wave lengths can be removed from the monochromator.

[0005] Spectrometer arrangements built on the basis of this manner have been known for a lengthy time. A simple example thereof is taught by DE 168 60 021.

[0006] The controllable spatial angular changing of the radiation is achieved by means of mechanical, rotational movements of a diffraction grating or of the dispersion prism and/or by means of the turning of a mirror, which has additionally been interposed in the path of the beam. In accord with the state of the technology, the drive of such means is generally by stepping motors. The angular resolution correlates itself, in this arrangement, with the appropriately incremented step subdivisions of the motor. Additional refinement practices and corrective measures can be achieved by relying on additional piezo actuators.

[0007] Extensive scanning periods, that is, long responsive functioning as well as big volume, prove to be mechanically expensive. These are disturbance prone and result from an inevitable response to the disadvantages of the design practices immediately described above.

[0008] Some of these disadvantages, can be avoided with heavy, base constructions exhibiting inertia problems, wherein, for each sensor value, the exact mechanical angular position is determined, and thereby, measurements can be assigned to the respective wave lengths. Thus, in DE 43 17 948 a spring-biased pivotal mirror is installed, the special disadvantage of which, is the extensive cost for angle control and/or measurement thereof.

[0009] Generally, the monochromators of a mechanically moved component design have the disadvantage, that their operative life at a required precision is limited and/or the bearing structures of these components require high manufacturing and adjustment costs.

[0010] It is the purpose of the invention, to make available a simple arrangement for monochromators which operate in accord with the mechanical selection principal and eliminate the above mentioned disadvantages. This purpose is achieved by the arrangements presented in the claims based on the features in accord with the invention. Further advantageous variants of the invented arrangement, as well as preferred procedures for the operation of the same, are to be found in the subordinate claims.

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[0011] In accord with the invention, in the beam path of the monochromator. as stated in the principal concept of claim 1, is inserted a monolithic, micromechanical, pivotal mirror. with the help of which, augmented by its angular positioning, a beam of a desired wavelength can be selected.

[0012] The use of such a monolithic micromechanical mirror has been practiced up to this time, only in connection with laser television. The manufacture and the operation of the same are adequately disclosed by the applications DE 41 00 358 and DE 42 24 599. The drive of this mirror can be accomplished either galvanically or preferably electrostatically. The actual angular positioning is advantageously measured by capacitative means.

[0013] The advantage of this arrangement represents an especially simpler, more economical, space saving and rugged construction of the monochromator, simultaneously accompanied with a shorter outlay in an assigned control system. Further, a stepless angle adjustment can be achieved therewith. The monolithic, single crystal construction of the tilting mirror brings about also a theoretically, unlimited operative life even with optional freedom to make repeated runs of operation.

[0014] A combination of several monochromators with the usage of one micromechanical mirror offers, beside a simple construction, especially the advantage of the exact wavelength-synchronization of independent channels, which, for example, is of considerable importance where making measurements of a beam source or for circuits, each with a plurality of monochromators.

[0015] In a further embodiment of the invention, provision has been made, that the diffraction grating be placed directly on the surface of the said micromechanical mirror. Beside the simplification of the monochromator arrangement, the special advantage lies in the thoroughly technologically derived manufacture of the mirror-grating-combination.

[0016] An advantageous variant of the invention retains the basic formation of this integrated, diffraction grating in such a manner, that the said grating can be made by means of a hologram type designed, localized orientated, otherwise plane grating. Under certain circumstances, in this matter, lenses, in particular also concave mirrors, can be installed to achieve beam formation.

[0017] The invented monochromator arrangement allows itself to be used particularly for spectrometer applications, wherein specific beam detectors are placed directly at the beam exit slot, or indirectly following additional test arrangements, or, indeed, totally taking the place of such openings on the exit side.

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[0018] In the case of a procedure for the operation of the invented monochromator, the fact is made use of, in that the monolithic, micromechanical mirror, because of its hysteresis-free torsion bands, and in connection with its inertial moment, possesses a resonance frequency at a considerably higher frequency and as a result, a harmonic incitation at this frequency acts to provide an extremely high stability and predictability of the flow of the motion. The advantage is to be found in a high precision of the temporal wavelength resolution, in spite of more discrete and/or less exact mirror angle measurements. Additionally, there is made available during an extreme resonance increase a greater deflection range and therewith a broader and more workable wavelength range.

[0019] The invention is, in the following, more closely described and explained by the use of embodiment examples depicted in illustrations. There is shown in:

Fig. 1 the principal construction of the invented monochromator,

Fig. 2 a variant of this monochromator on the basis of a diffractive grating,

Fig. 3 a monochromator arrangement with an integrated diffractive grating on a pivotal mirror,

Fig. 4 a double monochromator with a common diffractive grating on the pivotal mirror, and

Fig. 5 a monochromator with an imaging diffractive grating on the pivotal mirror

[0019 (continued)]

For the formation of the path of the beam in an exemplary monochromator, in accord with Figs. 1 and 2, there are placed in position:

-- an incident side spatial filter, comprised of a slit-shaped optical fitting consisting of, for example, an orifice, (1) or a fiber coupling (10) or possibly of an optically imaging element such as, for instance, a collimator mirror (3) or a lens system (7),

-- a dispersing element, this being a prism (4) or a diffractive grating (8)

-- a micromechanical pivotal mirror (5), inclusive of a mirror drive (6) for spatial sequential wavelength selection with typical, lateral outside dimensioning of 5 mm x 5 mm.

-- an exit area spatial filter of imaging-optical qualities (3; 7) with an slotlike orifice (2) or a sufficiently narrowly dimensioned sensor (11) in the focal plane.

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[0021] The polychrome beam, which has been routed through the monochromator of Fig. 1 is rendered parallel with the aid of the spatial filter. The now corrected beam, runs through the dispersion prism (4) and experiences a first wavelength related splitting of direction. The beam direction of one of each wavelength component of the polychromatic incident beam is directed through the micromechanical mirror 5 in such a manner, that the beam, so directed, once again passes through the prism (4) and is subjected to a renewed wavelength related directional change. With the aid of the spatial filter (3, 2) on the exit side, the parallel partial beams are focused and each, in accord with the angular setting of the mirror (5) is selected on the basis of wavelength and is released from the combined spectrum.

[0022] Optionally, a spatial arrangement of these optical elements may be appropriately varied, for example, as autocollimation spectrograph, in accord with Figs 1 to 5. The arrangement of Figs 1 and 2 serves, however, the known advantage of the optical angle doubling of a mechanical mirror deflection.

[0023] Fig. 3 shows a monochromator arrangement with an inlet and an outlet spatial filter (1, 7; 7, 2) as well as a pivotal mirror (5) and a diffraction grating (9), whereby this diffraction grating, in accord with methods of microstructuring, is placed, in accord with the invention, directly on the surface of the micromechanical pivotal mirror, and, in particular, in parallel between the grating lines and the axis of rotation of the mirror. In the embodiment example, the diffractive grating is implanted as a "phase-grating". In this arrangement, in accord with each required degree of diffractive action, the diffractive grating can be supplied with another appropriate grating-periodic surface structure, insofar as these are real in the framework of normal fabrication technology. The especial action of this micromechanical integration of the diffraction grating lies within the possibilities for a shortening of the optical path of the beam and aids the therefrom resulting miniaturizing of the monochromator. Beyond this, the technologically thoroughness of the manufacturing of the mirror-grating combination offers essential economic advantages even in the mounting of a monochromator. The grating constants attainable in normal fabrication methods run in the general magnitude of 1 μm and allow special wavelength intervals of the monochromators in the VIS (Visible Imaging System) and the NIR (Near Infra Red) areas.

[0024] An additional simplification of the construction of the monochromator is shown with the aid of the schematics of Fig. 5. The integrated diffractive grating (13) upon the micromechanical pivotal mirror (5) possesses such a dependence upon the positioning of its lateral grating periodicity, that it acts in a diffractive-optical imaging manner. The entry and exit side spatial filters include principally slot orifices (1, 2).

[0025] The hologram type, diffractive grating structure one obtains for the first order of diffraction for design, for example from a cross-section of a tilting-mirror surface with a family of ellipsoids of rotation about two characteristic construction points used as ellipsoid foci, whereby the optical total light path

length from the first construction point to the ellipsoid and back to the second construction point differ from one another by a constant wavelength.

[0026] Each coupled, divergent beam portion which has passed through the entry slot, after impacting the grating structure, and in accord with its wavelength and especially in accord with the local grating period and orientation is diffracted to a defined, wavelength-related focus, whereby the exit slot selects one of these foci for the beam to disengage.

[0027] In accord with the relative angle of the diffraction grating to the slot, there is formed, in accord with the Scheme of a Rowland's Circle, slight aberrations of the wave-length related foci for the fixed slot plane (1, 2). The therefrom resulting debilitation of the spectral dissociation can, however, in a case of a small deviating release angularity, and according to the application case, be tolerated by favoring the simplified method of construction, since additional imaging elements have been removed.

[0028] Fig. 4, demonstrates the advantageous arrangement of a common micromechanical pivotal mirror (5) – here, for example with an integrated diffraction grating (9) – serving simultaneously as a disengagement or dispersion unit for two advantageously identically built monochromator partial arrangements. The monochromators presented in the profile view are here combined to a double monochromator which is stray-light poor, this being done advantageously by means of subtractive row shifting. These are combined as said, in that the beam exit (2) of the first monochromator has been bound by means of an auxiliary mirror (12) to the beam coupling (2) of the second monochromator. The required synchronous wavelength selection guarantees an exact, reproducible, spectral throughput with the double-monochromators even in a case of a possibly lesser mirror angle reproducibility.

[0029] In general, by means of this invented simplification, additional mirror drives and mirror control devices are no longer necessary. Further, this exact synchronization of two identically constructed, independent monochromator channels offers considerable advantages for measurement arrangements, in which a reference channel demands, that a beam source must be controlled in its spectral and temporal duration.

[0030] The schematically drawn pivotal mirrors (5) possess, for example, a reversed electrode unit (6) to fulfill the purpose of an electrostatic drive. From the literature, it is further made known, how to determine the actual angular position of the said pivotal mirror capacitatively by means of the same electrodes. This angular measurement attainable by simple mechanical means has, however, the disadvantage of a low value angular resolution, which is limited by a small linearity and a high portion of noise because of the very small electrode surface.

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[0031] Pivotal mirrors, which are made from single crystal silicon are monolithically bound by torsion bands with an affixed carrier, this structure provides a hysteresis-free spring constant c. In coaction with a surface-lag moment J of the mirror, which resolves into a mechanical vibration series $f = 2\pi c/J$. The characteristic vibration at this frequency has a high resonance value, since, because of the freedom from hysteresis the damping of the mechanical vibration is very small. In the case of activation of the pivotal mirror by means of external vibration at even this inherent frequency ω, it is possible with even the relatively weak electrostatic driving forces to attain high dissociated angles γ_o, Phase ϕ and possibly exact resonance frequency ω in order to achieve about 2° to 3°. The resonance vibration is, under these conditions, relatively insensitive in relation to external mechanical disturbances . Bringing in to the picture the adiabatic compression forces of the air buffer between the electrodes and the mirror allows the following equation to be made: $M = c \cdot \gamma = J \frac{d^2\gamma}{dt^2} + F_{adiab}(\gamma) + F_{ext}\left(\gamma, sin(\omega \cdot t + \varphi)\right)$ which can be solved by approach approximation, namely, $\gamma(t) = \gamma_o \cdot sin(\omega \cdot t + \varphi)$.

[0032] In the course of the invented procedure for the preferred operation of the micromechanical pivotal mirror, the pivotal mirror is periodically mechanically activated at its own resonance frequency (normally between 100 Hz and 1000 Hz), whereby the immediate release angle γ of the mirror is measured quasicontinually or at individual, discrete points of time, namely t_i. The so obtained angle values are correlated with the theoretically obtained solution of the motion equation, in order that the parametric vibratory amplitude γ_0 Phase ϕ and possibly the exact resonance frequency ω by means of a numeric evaluation can be determined in the best possible manner.

[0033] With these parameters established, the evaluation, computed by means of the above solution of the movement equation at that optional point in time t the actual deviation angle $\gamma(t)$ and, further by means by the angularity of the refraction the actual selected wavelength $\lambda(t)$, by means of :

$$\sin\left(\alpha + \gamma(t)\right) = \sin\left(\beta - (\gamma t)\right) + N \cdot \left(\frac{\lambda(t)}{g}\right);$$

where:

g serves as the grating constant, and

α and β respectively represent the incidental and diffraction angle of the grating at a zero setting of the pivotal mirror.

[0034] In a case of a separated arrangement of the pivotal mirror and the diffraction grating, as in Fig. 2, the optical doubling of the deflection angle in relation to the release angle of the mirror should be carefully considered.

[0035] In accord with the invented operational procedure, it is especially possible that the trigger point t_k can be derived for a monochromatic beam measurement S_k in a case of preselected wavelengths λk,

further, it is possible, that the mirror drive, for the retention of the resonance vibration, is to control in an exact phase-synchronous manner. Conversely, it is also possible, that to each beam radiation-value S_k its respective wavelength λ_k could be assigned, which establishes subsequent, numerical interpolation of the measurement value to preselected wavelengths.

[0036] This operation procedure thus elevates the precision of the determination of wave length and therewith, in general, essentially, the spectral resolution of the invented spectrometer. For a demanded resolution it is also possible that the primary angle measurement of the pivotal mirror can be determined with the simplest relatively mathematically approximation means.

CLAIMS

Claimed is:

1. A monochromator with at least one immobile spatial filter for the limitation of the spatial angle zone of the spatial angle field of influence of the incident polychromatic radiation, a dispersive element for spatial angle changing of this radiation related to spectral elements, as well as at least one additional, stationarily affixed spatial filter for the reception of the conducted monochromatic beam portion found within the spatial angle neighborhood, as well as a means for the controllable beam related geometric spatial angle alteration, therein characterized, in that this means for the change of direction of the course of the beam is a monolithic, micromechanical pivotal mirror.

2. A monochromator in accord with claim 1, with a plurality of beam-geometrically independent channels, therein characterized, in that a single, common micromechanical pivotal mirror is included.

3. A monochromator in accord with claims 1 and 2, therein characterized, in that on the surface of the micromechanical pivotal mirror, a flat diffraction grating is integrated.

4. A monochromator in accord with claim 3, therein characterized, in that the flat diffraction grating on the surface of the micromechanical pivotal mirror possesses a characteristic local grating period and grating orientation, so that the diffraction grating possesses beam-geometric image building characteristics as a part of the spatial filter.

5. A spectrometer with beam detectors and at least one monochromator in accord with the claims 1 to 4.

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6. A procedure for the operation of a spectrometer arrangement in accord with claim 5 with an established numerical evaluation, therein characterized,

   in that the pivotal movements of the micromechanical pivotal mirror coacting with its mechanical resonance frequency, are so stimulated, that at discrete points of time the mirror angle position is measured,

   in that at discrete points of time the mirror angular position is measured,

   in that the measured angular position of the mirror can be correlated parameterized solution of the motion equation of the micromechanical mirror for the purpose of attaining the numeric movement parameter,

   in that with the aid of this said movement parameter, it becomes possible to numerically determine the exact periodic run of time of the respective, detectable wavelengths, whereby either the beam detection values, which respectively are assigned the determined wave lengths and/or the beam detection, upon reaching a preset wavelength is triggered, and further, optionally, the degree of excitation of the pivotal mirror is phase-synchronously controlled.

Hereto connected, 1 page of Figures.

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